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Space Station Freedom Beta Gimbal Control Via Sensitivity Models

David A. Schoenwald
Martin Marietta Energy Systems
Oak Ridge, Tennessee

Umit Ozguner
Ohio State University
Columbus, Ohio

and

Ronald E. Graham
Lewis Research Center
Cleveland, Ohio

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David A. Schoenwald
Martin Marietta Energy Systems
Oak Ridge, Tennessee

Ümit Özgüner
Department of Electrical Engineering
The Ohio State University
Columbus, Ohio

and

Ronald E. Graham
National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135

SUMMARY

Tracking control of the Space Station Freedom solar array beta gimbals is investigated. Of particular interest is the issue of control in the presence of uncertainty in gimbal friction parameters. Sensitivity functions have been incorporated into the feedback loop to desensitize the gimbal control law to parameter variations. Simulation results indicated that one such sensitivity function improves the closed-loop performance of the gimbals in the presence of unexpected friction parameter dispersions.

INTRODUCTION

The problem of control of mechanical joints in the presence of friction has been of considerable interest for years. Most large mechanical systems require actuation, and friction is inevitably present in such actuators. A principal issue in pointing control is the modeling of friction in gimbaling joints (ref. 5). Rockwell International's Rocketdyne Division, with responsibility for the Space Station Freedom's solar array beta gimbals, has investigated the dynamics of the beta gimbals (refs. 2 and 6) in the presence of four types of friction: Coulomb, Dahl, static and viscous.

Both Coulomb and Dahl friction are nonlinear discontinuous functions of gimbal velocity, while static friction represents a dead zone. In this study, a quadratic cost criterion is applied to control design for the beta gimbals. The cost criterion penalizes tracking deviations and energy input to the motor.

A term may be included in such a cost criterion which takes into account uncertainty in friction parameters, with the use of a sensitivity model in the feedback loop. The sensitivity model derives the partial derivative of the state with respect to uncertain parameters, and provides a measure of change in state with parameter dispersions.

Friction models incorporated in the gimbal dynamics are based on theoretical and experimental analysis performed by NASA Lewis Research Center and by Rocketdyne. Viscous friction is linear, and therefore simple to model. Coulomb friction is a constant torque that opposes the direction of gimbal velocity. Dahl friction (ref. 3) has a first-order dependence on the direction of gimbal velocity and is also highly nonlinear. Static friction is considered to be an algebraic inequality, not present directly in the dynamics. In the case of each form of friction, the tools of sensitivity analysis are applicable.

The procedure followed here is as follows: (1) Using the known beta gimbal dynamics, sensitivity models are derived for each uncertain parameter. (2) A linear control law is applied which incorporates a penalty on the sensitivity functions. (3) Simulation results are used to assess and reduce the sensitivity models.

NOMENCLATURE

Name	Description	Units
β	gimbal angle	radians
I_M	motor current	amps
J_A	array axis moment of inertia	in-lbf-sec^2
L_M	motor inductance	H
R_M	motor resistance	Ω
K_{BEMF}	motor back-EMF constant	volt-sec
K_T	motor current-to-torque constant	in-lbf/amps
K_V	viscous friction	in-lbf-sec
T_A	applied gimbal torque	in-lbf
T_C	Coulomb friction	in-lbf
T_D	Dahl friction	in-lbf
σ	slope of Dahl friction model	in-lbf
T_{DL}	Dahl friction limit	in-lbf
T_S	static friction	in-lbf
T_F	total friction torque	in-lbf
T_M	motor torque	in-lbf
T_V	viscous friction	in-lbf
V_M	motor voltage	volts

SENSITIVITY MODELS

The known beta gimbal dynamics are shown in block diagram form in figure 1. The block diagram (refs. 2 and 6) may be used to prepare the model's governing equations:

$$
\begin{aligned}
\textit{If} \quad T_s \quad &> \quad | K_T I_M + J_A \ddot{\beta} | \quad \textit{then} \\
\dot{I}_M \quad &= -\frac{K_{BEMF}}{L_M} \dot{\beta} - \frac{R_M}{L_M} I_M + \frac{1}{L_M} V_M \\
\ddot{\beta} \quad &= 0 \\
\dot{T}_D \quad &= 0 \\
\textit{Else} \quad \dot{I}_M \quad &= -\frac{K_{BEMF}}{L_M} \dot{\beta} - \frac{R_M}{L_M} I_M + \frac{1}{L_M} V_M \\
\ddot{\beta} \quad &= \frac{K_T}{J_A} I_M - \frac{K_V}{J_A} \dot{\beta} - \frac{T_C}{J_A} sign(\dot{\beta}) - \frac{1}{J_A} T_D \\
\dot{T}_D \quad &= \left[\sigma \left| 1 - \frac{T_D}{T_{DL}} sign(\dot{\beta}) \right|^2 sign(1 - \frac{T_D}{T_{DL}} sign(\dot{\beta})) \right] \dot{\beta}
\end{aligned}
\tag{1}
$$

The Dahl friction term (ref. 3) represents bearing friction and is hysteretic. It can be represented more simply than in equation (1), although the above representation is widely used in ball bearing simulation studies.

Equation (1) can be represented by a state-space description. In the case when the gimbals are moving,

$$
\begin{aligned}
\dot{X} \quad &= f(X,\alpha) + g(X)u \\
\textit{where} \ X \quad &= \left[I_M \ \ \beta \ \ \dot{\beta} \ \ T_D \right]^T \\
u \quad &= V_M \\
\alpha \quad &= \left[K_{VS} \ \ T_C \ \ T_{DL} \right]^T
\end{aligned}
\tag{2}
$$

and f($\mathbf{X}$,α) and g($\mathbf{X}$) are obtained directly from equation (1), the "else" condition.

The sensitivity functions are defined as the partial derivative of the state vector with respect to the parameter of interest (ref. 4). They are generated as follows:

$$\frac{\partial \dot{\mathbf{X}}}{\partial \alpha_i} = \frac{\partial f}{\partial \mathbf{X}} \frac{\partial \mathbf{X}}{\partial \alpha_i} + \frac{\partial f}{\partial \alpha_i} \quad (i = 1,2,3)$$

$$\frac{\partial f}{\partial \mathbf{X}} = \begin{bmatrix} -\frac{R_M}{L_M} & 0 & -\frac{K_{BEMF}}{L_M} & 0 \\ 0 & 0 & 1 & 0 \\ \frac{K_T}{J_A} & 0 & -\frac{\alpha_1}{J_A} & -\frac{1}{J_A} \\ 0 & 0 & \tau_1(\mathbf{X},\boldsymbol{\alpha}) & \tau_2(\mathbf{X},\boldsymbol{\alpha}) \end{bmatrix}$$

$$\tau_1(\mathbf{X},\boldsymbol{\alpha}) = \sigma \left[1 - \frac{x_4}{\alpha_3} sgn(x_3) \right]^2 sgn[1 - \frac{x_4}{\alpha_3} sgn(x_3)] \qquad (3)$$

$$\tau_2(\mathbf{X},\boldsymbol{\alpha}) = -2\sigma\ [1 - \frac{x_4}{\alpha_3} sgn(x_3)] \frac{sgn(x_3)}{\alpha_3} sgn[1 - \frac{x_4}{\alpha_3} sgn(x_3)]\ x_3$$

$$\frac{\partial f}{\partial \alpha_1} = [\,0 \quad 0 \ -x_3 \quad 0\,]^T$$

$$\frac{\partial f}{\partial \alpha_2} = [\,0 \quad 0 \ -sgn(x_3) \quad 0\,]^T$$

$$\frac{\partial f}{\partial \alpha_3} = \left[\,0 \quad 0 \quad 0 \ -\tau_2(\mathbf{X},\boldsymbol{\alpha})\frac{x_4}{\alpha_3}\,\right]^T$$

This is linear in the sensitivity functions although nonlinear in **X**. The first of equation (3) is a linear, though time-varying, differential equation.

The sensitivity functions are generally of interest in a neighborhood of some nominal parameter values. This implies that for all instances of α_i the sensitivity model would be known. This is useful for small deviations in the friction parameters from their assumed nominal values. "Small deviations" are considered here to be within 25 percent of nominal. For larger dispersions, second-order sensitivity functions may be needed (ref. 4), and those are a straightforward extension of equation (3).

Having obtained the sensitivity model, to provide a linear control law that penalizes sensitivity merely involves a feedback gain matrix on the sensitivity, as in figure 2. Simulations of the model shown in figure 2 were performed, in order to assess gimbal control performance improvement due to sensitivity feedback.

SIMULATION RESULTS

A truth model was prepared in FORTRAN, containing equation (2). A PID control law was designed to enable the gimbals to perform well based on nominal values of friction parameters, chosen as follows:

Name	Value
K_{VS}	81.4
T_C	6.0
T_{DL}	24.0
T_S	12.0
σ	900.0

The PID control law had the following gains:

Gain	Value	Units
proportional	7430	volts/rad
integral	250	volts/rad-sec
derivative	17530	volts-sec/rad

To incorporate all sensitivity functions would be equivalent to implementing a 12th-order filter in the feedback path, requiring more constants than are available to the gimbal controllers (ref. 7) in flight. The analysis was therefore used to select only those sensitivity functions which offered the greatest benefit to dynamical response.

Gimbal position sensitivity functions offered little impact. Dahl friction and motor current states were found to be less important than gimbal velocity. Further, Coulomb and Dahl friction sensitivity parameters require differentiation across discontinuities, which can be implemented but should be avoided in this case due to resource limitations. For these reasons, only one sensitivity function was implemented in the control law: that of gimbal velocity (x_3) with respect to viscous friction (α_1).

Simulation results show that feedback of this sensitivity function will not only reduce control sensitivity to variations in viscous friction, but Coulomb friction variations as well. The function will not improve performance under Dahl or static friction dispersions, but will not degrade performance either.

For a gain of 50 V-in-lbf-sec^2/rad on this function, the following is a comparison of performance (in terms of percent overshoot and settling time) for a unit step command to gimbal angle, for cases with (W) and without (W/O) the sensitivity function feedback, for a 20 percent dispersion in K_V:

Indicator	Nominal		20 percent viscous dispersion			
			increase		decrease	
	W	W/O	W	W/O	W	W/O
overshoot (percent)	10	10	8	8	9	9
settling time (s)	28	35	28	35	33	42

The following is a comparison of performance for a unit step command to gimbal angle, for cases with and without the sensitivity function feedback, for a 20 percent dispersion in T_C:

Indicator	Nominal		20 percent Coulomb dispersion			
			increase		decrease	
	W	W/O	W	W/O	W	W/O
overshoot (percent)	10	10	8	8	8	8
settling time (s)	28	35	30	30	30	90

As can be seen from these two performance summaries, the only case in which no measurable performance improvement can be seen is that of a 20 percent increase in T_C. Even in that case, there is no performance degradation.

In each case, the sensitivity feedback gain is maintained at 50. This gain can be changed as the designers gain confidence in friction parameter values. If, for instance, there is a tolerance of 5 percent or less expected in Coulomb and viscous friction parameters, then this feedback term will not improve performance much. If, however, the tolerance is as high as 25 percent, then the introduction of this term to the gimbal control law will improve performance a good deal.

CONCLUSIONS

The addition of a single sensitivity function to the feedback control law, along with an existing PID controller, improves settling time without increasing overshoot in step response. Beta gimbal dynamics were simulated both with and without this sensitivity function. Simulation results showed improved performance for parameter variations in viscous, Coulomb and Dahl friction from nominal values.

The sensitivity function, that of gimbal velocity with respect to viscous friction coefficient, is a recommended addition to the beta gimbal control law algorithm for Space Station Freedom solar array pointing control.

Further work, if any, should consider the inclusion of other degrees of freedom, such as station body rotations and array flexible modes.

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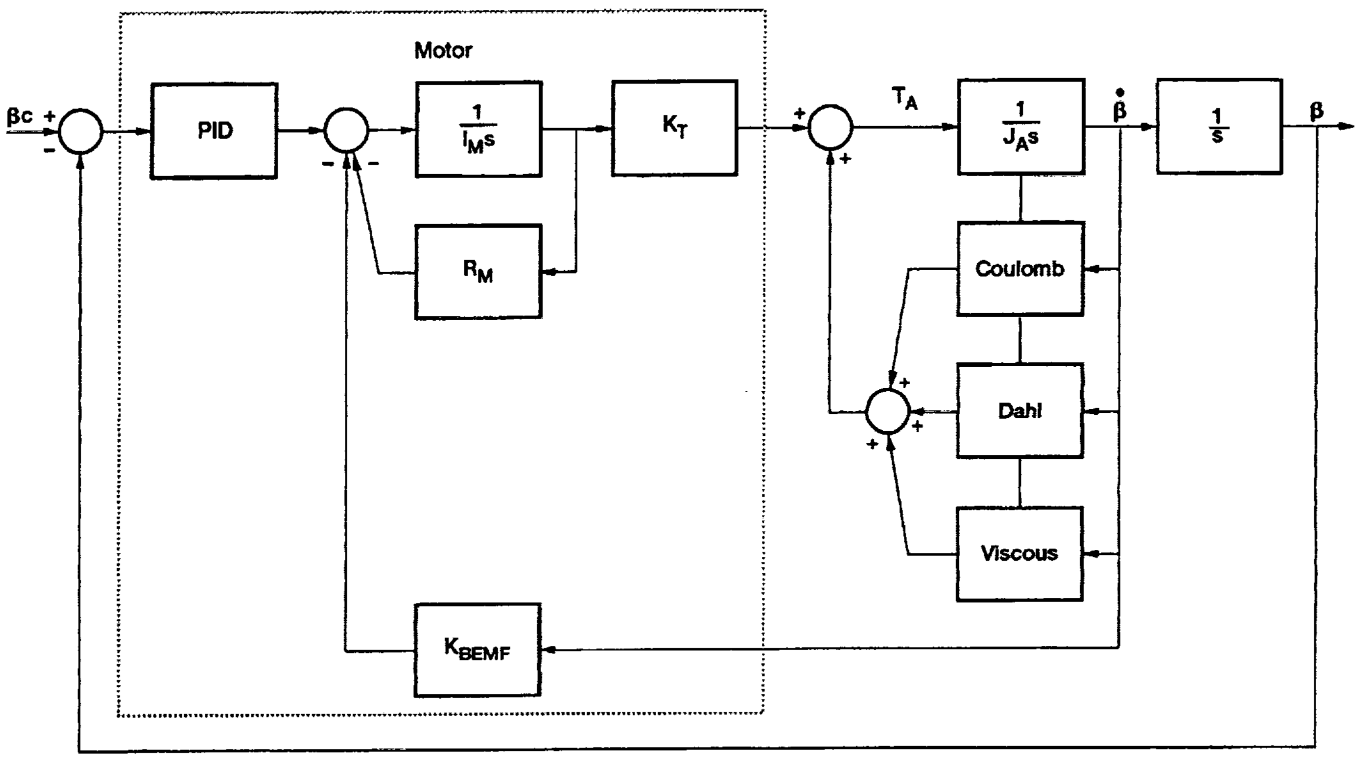

Figure 1.—Block diagram of beta gimbal control and dynamics without sensitivity.

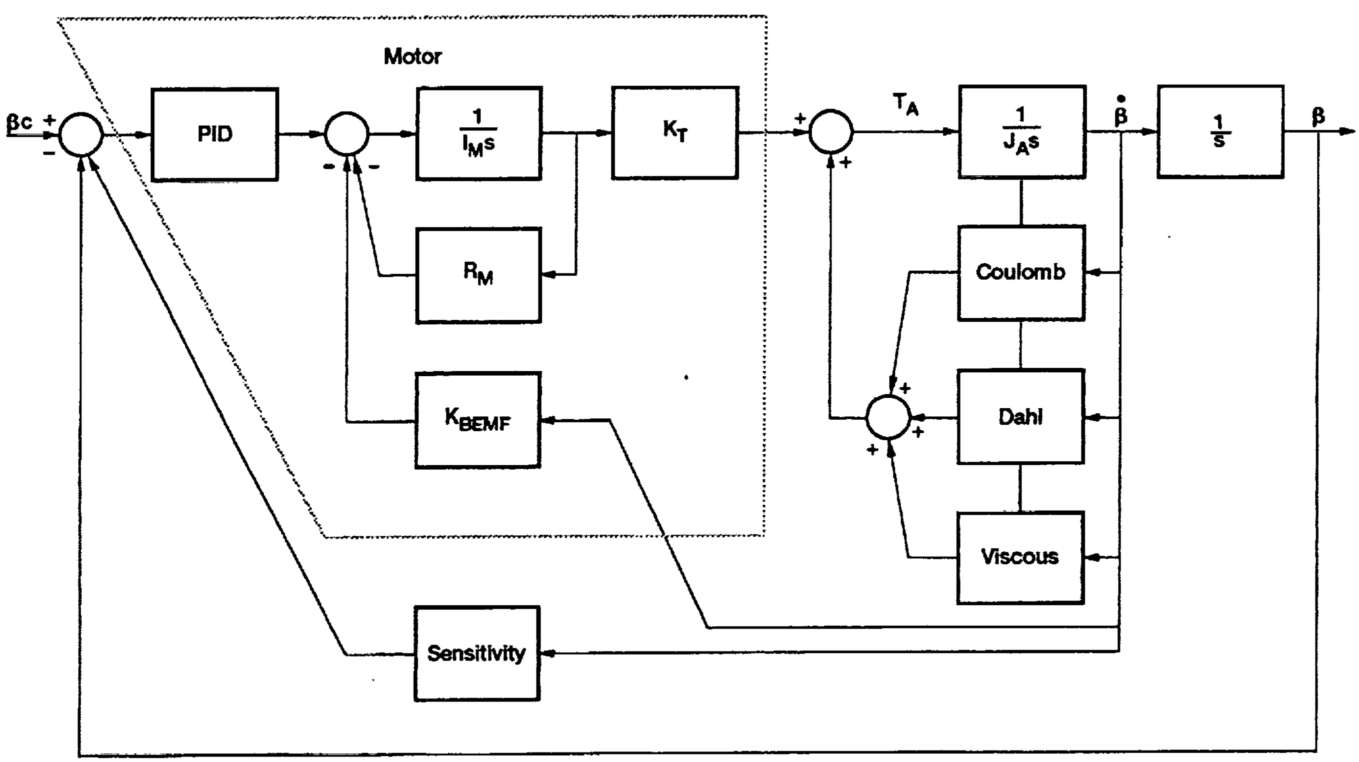

Figure 2.—Block diagram with sensitivity feedback of gimbal velocity.

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David A. Schoenwald, Umit Ozguner, and Ronald E. Graham

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David A. Schoenwald, Martin Marietta Energy Systems, Oak Ridge, Tennessee, and Umit Ozguner, Ohio State University, Department of Electrical Engineering, Columbus, Ohio 44320, and Ronald E. Graham, NASA Lewis Research Center, Cleveland, Ohio. Responsible person, Ronald E. Graham, (216) 433–5178.

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